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Auction Design and the Success of National 3G Spectrum Auctions*†

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Abstract

This study empirically examines a sample of national wireless spectrum assignments for the period 2000-2007 to identify the sources of revenue variations. An econometric model that recognises the censored nature of the sample relates per capita winning bid (per Mhz) values to auction design variables (license award process), national and mobile market conditions, spectrum package attributes and post-award obligations identified from national regulatory authority tender documents. The analysis reveals that most auction design variables independently impact on realized 3G spectrum auction revenue in a manner consistent with auction theory.

JEL Classification: D44; L96

Keywords: Wireless telephone markets, 3G spectrum auctions, spectrum bid price

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1. Introduction

During the five decades since the seminal work of Friedman (1956) and Vickrey (1961), auction theory has developed into an established field of economic research. However, the application of this accumulated knowledge to allocate operating rights in telecommunication markets only occurred in 1990 with the New Zealand government's decision to license spectrum by auction. The argument for using the 'price system' (via an auction) to allocate spectrum licences is premised on economic efficiency arguments that: (a) it eliminates the rent dissipation associated with 'beauty contest' awards; (b) assignment of licences is made to most productive suppliers; and (c) generated public revenues displace taxes (Cramton, 2001). Currently, auctions are equally the most commonly used mechanism (along with administrative processes or beauty contests) to assign wireless spectrum in national telecommunications markets. During the period 2000-2007, 83 national 3G spectrum licenses are assigned via auctions organized by national regulatory authorities (NRAs) in twenty countries.

Although the use of auctions to (re)organize telecommunication markets is only recent, national spectrum auction outcomes vary markedly in terms of revenue raised by country and time period.[1] For instance, revenue (per capita) obtained from the auction of 3G licenses in the year 2000 are as high as €650 in the United Kingdom (UK), but with values of €100 (Austria), €615 (Germany), €240 (Italy), €170 (the Netherlands), and €20 (Switzerland) also realized. Clearly, such huge revenue differences are not explained solely by national mobile market and economic conditions. Paul Klemperer, an advisor (together with Ken Binmore) to UK government's Radiocommunications Agency on the design and conduct of one of the most successful spectrum auctions, remarks in Klemperer (2002a, b) that it is mainly the NRAs' inappropriate choice of auction design that led to the failure in some of the early European spectrum auctions. Also, an appraisal of these auctions is made by Peter Cramton (2001), who advised governments for several telecommunications auctions in the Australia, Canada and the United States.[2] While these surveys provided helpful insight as to what went wrong and what really matters in the European spectrum auctions, these analyses lacked rigorous empirical examination to identify statistically the impact of auction design and

[1] Based on these arguments, a literature on the implementation of auctions emerged, with auction 'successes' typically measured by the magnitude of license receipts. Recently, Hazlett and Muñoz (2009) demonstrate that the focus on revenue as a measure of success might be flawed.
[2] The United States Federal Communications Commission followed this example three years later.

license conditions (as specified in NRA tender documents) on realized revenues. The apparent need for such applied work is only recently acknowledged with the emergence of digital dividends from the release of spectrum from analogue TV switch off and the reallocation of spectrum bands to meet emerging fourth-generation wireless market needs. Accordingly, this study constructs an econometric model to examine the impact of national and mobile market conditions, spectrum package attributes, post-award obligations and a license award condition (viz., initial deposits requirements) on the winning bid prices observed in the 2000-2007 period for national 3G spectrum license auctions.

Importantly, the study's focus allows exploration of the impact of auction designs, rules and award processes on the realized revenues. The particular auction attributes analyzed (license award processes) are: number of bidders per license; availability of an activity rule; publicity of bid information; flexibility of the number of licenses; availability of package bidding; and the bid format (sealed or open). Study findings show that most of these license award/auction design variables independently impact on 3G spectrum auction revenues.

The contribution of this paper is twofold. First, a comprehensive empirical account of what matters for past spectrum auction 'success' (in terms of realized revenue) is provided. Second, the empirical findings concerning auction design processes and realized revenue provides a natural test of several game-theoretic predictions of the auction theory.[3] Received empirical analysis of auction data generally tests game-theoretic predictions conditioned on the informational context. A strand of applied literature (Mead 1967; Smith 1977; Gaver and Zimmerman 1977; Heckman 1977; Brannman et al. 1987) tests the empirical validity of the winner's curse - a phenomenon observed in the 'symmetric common value' model. Yet another strand (Mead 1967; Johnson 1979; Mead et al. 1981; Hansen 1985) tests the 'revenue equivalence theorem' - a prediction from the 'independent private value' model.[4] Clearly, an alternative approach to testing is to question the empirical validity of particular informational

[3] Thus, uncertainty about bidder valuations can take several forms: (a) every bidder may privately know the value of an object independently from the valuations of the other bidders (the independent private values case); and (b) bidder valuations can be interdependent., e.g., symmetric (in which the bidders have private signals about a common valuation) or asymmetric (in which only some bidders are completely informed about the common value of the object) common value. Auction theory is generally interested in the design of optimal mechanisms (consisting of a game-form involving a set of available bidder strategies, rules of the game and allocation rules) to sell an object to bidders whose valuations are unknown sellers and other bidders. In all informational situations, auction outcomes are determined via a non-cooperative game played by bidders under rules determined by their beliefs about the goods valuation and/or signals from other bidders.

[4] Laffont (1997) surveys a wide range of applied work with the auction data.

models conditional on the game theoretic restrictions or predictions of the auction theory. Both approaches are employed in interpreting empirical findings contained in this paper.

The remainder of the paper is organised as follows: Section 2 introduces factors that affect mobile network operator (MNO) spectrum valuations. Section 3 presents national spectrum national auction data and variables, and Section 4 presents the model. Section 5 contains model estimates and their interpretation. Section 6 concludes.

2. Factors affecting MNO Spectrum Valuations

An MNO $(\text{Operator}\,j)$ assesses an opportunity to acquire spectrum based on whether $r_{ij} - b_{ij} > 0$, where r_{ij} is the projected net revenue from use of spectrum package i (based on spectrum award conditions, and operating revenue and cost estimates) through the license period, and b_{ij} is the final spectrum bid price made by the operator for the spectrum resource. Further, the quantity $b_{ij} - b_{ij}^{min} > 0$ is the bid premium an operator offers to obtain the spectrum license, i.e., the excess above the reserve bid price (b_{i}^{min}) required by the NRA in the tender document. The award value must not only exceed the minimum required spectrum bid price but be the largest value among all bidders. The spectrum assignment is efficient when the bid price accurately reflects the underlying opportunity costs of the firm.[5] When $r_{ij} - b_{ij}^{min} < 0$ then no bid is made as the operator incurs losses in providing 3G service over the spectrum. From the published spectrum awards, data observable to the analyst is the winner's bid price, b_{ij}^{*}. When there is no bid (and hence no winner) b_{ij}^{*} is censored at a zero value.

Factors that potentially impact on the winning spectrum bid price that are identified by the literature include spectrum package attributes. Attributes considered in the analysis are: license duration (Klemperer, 2002a), whether an entrant must be awarded a license (Klemperer, 2002a), and the magnitude of the required minimum bid (reserve) price (Burguet and Sakovics, 1996; Klemperer, 2002a). Variables that describe the license award process include the competitiveness of the process (Klemperer, 2002b) and auction design variables, viz., whether: (a) there are activity rules; (b) information is made available at the end of each

[5] Standard auctions (at best) ensure that the bidder with the highest private value wins, rather than the highest social value. Private and social values diverge as the winners compete in a marketplace (Cramton, 2002: 608).

round; (c) there is a single sealed-bid; (d) license number is determined endogenously; and (e) if package bidding is allowed.

Additionally, operator post-award financial and network performance obligations potentially impact on the spectrum bid price. A financial performance obligation variable considered is annual license fees based on a proportion of 3G revenues (Bauer, 2003), while network performance obligation variables included are infrastructure sharing, and a variable that accounts for population coverage and timing (Klemperer, 2002b). Finally, exogenous variables that reflect national economic and mobile market conditions, respectively, are national income (Börgers and Dustmann, 2003), market size and the competitiveness of domestic mobile telephony markets (Klemperer, 2002a).[6]

3. Data and Variables

The first 3G spectrum license auctions are held in Western Europe in 2000.[7] This study examines a sample of 81 licenses from 21 national auctions for 2000–2007. These data are sourced from the DotEcon (2008) Spectrum Awards Database. Table 1 and Table 2, respectively, present the definition, mean and standard deviation for the dependent and independent variables used in the empirical analysis. The dependent variable in this study is the winning bid for spectrum (measured per MHz, per million populations). The variable is typically considered by economists to reflect the value of the spectrum package to the winning operator. In particular, higher revenues arise from product market extension to 3G spectrum, thus adding revenue streams otherwise not feasible from current activities. Synergistic benefits also arise from lower costs (e.g., savings may occur through improved productivity or network economies).[8] Either source of benefits potentially flow through to profit.

[6] Spectrum lot size and licence availability are implicitly controlled for in the regression equation. In particular, the dependent variable (WBID) is adjusted for the amount of spectrum in each licence. Namely, the winning bid is US$m per MHz per million population. The number of licences up for auction enters via the competition variable ACOMP. Namely, ACOMP = Licences/Bidders. Additionally, an anonymous referee has pointed out that the availability of substitutable spectrum now and in the future is likely to affect spectrum valuations.
[7] Finland is the first country to assign 3G spectrum via a beauty contest in 1999.
[8] The spectral efficiency is the number of bits that can be sent per second over a channel of a given bandwidth (Gruber, 2001: 62).

Table 1. Dependent Variable Summary Statistics, 2000–2007

Variable	Definition	Mean	Std Dev.
WBID	= Spectrum payment /MHz /million population (US$m)	0.88	1.33

Table 1 indicates there is substantial variation in WBID values across national assignments. Given the impact WBID values have on auction revenue and network deployment, identifying the source of this variation is important. Independent variables (listed in Table 2) which are proposed to explain WBID are divided into the categories: national economic and mobile market; spectrum package attributes; post-award financial obligations; post-award network deployment obligations; and license award process.

Table 2. Independent Variable Summary Statistics, 2000–2007

Variable	Definition	Mean	Std Dev.
National economic and mobile market			
INCOME	= Real GDP per capita (US$ PPP)	21,607	9,564
MARKET	= Size of population covered by license (millions)	346.18	504.19
MCOMP	= Inverse of one plus the number of facilities-based operators	0.22	0.04
SHIFT	= 1, if auction is held in 2001–2007; = 0, otherwise	0.62	0.49
Spectrum package attributes			
DURATION	= License term (years)	17.95	2.86
ENTRANT	= 1, if at least one license must be awarded to entrant; = 0, otherwise	0.12	0.33
RESERVE	= Minimum allowable spectrum bid price (US$ millions)	184.81	444.16
Post-award financial obligations			
PERCENT	= Mean annual license fee (% of 3G revenue)	0.22	0.68
Post-award network deployment obligations			
DEPLOY	= % of population to be covered by license/years to achieve cover	0.12	0.08
SHARE	= 1, if infrastructure sharing is imposed; = 0, otherwise	0.33	0.47
License award process			
ACOMP	= Bidders to available licenses (ratio)	1.21	0.59
ACTIVITY	= 1, if there is an activity rule; = 0, otherwise	0.62	0.49
INFO	= 1, if bid information made public every round; = 0, otherwise	0.38	0.49
NUMBER	= 1, if license number is exogenous; = 0, otherwise	0.74	0.44
PACKAGE	= 1, if package bidding is allowed; = 0, otherwise	0.27	0.45
SEALED	= 1, if the auction is sealed-bid; = 0, otherwise	0.20	0.40

Table 3 lists total auctions, number of assigned licenses and average WBID values by year. The majority of assigned licenses (60 of 81) are assigned during 2000–2001.

Table 3. Selected Auction Summary Data by Year, 2000–2007

Year	Auctions	Licenses Assigned	Mean Annual WBID
2000	6	31	1.95
2001	7	29	0.25
2002	1	5	0.37
2003	0	0	–
2004	0	0	–
2005	3	5	0.26
2006	2	6	0.05
2007	2	5	0.05
Sample	**21**	**81**	**0.88**

Table 3 shows that spectrum winning bids attenuate through time. Indeed, all WBID values greater than the sample mean (0.88) occur in 2000, probably due to overly optimistic expectations about the profitability of 3G service markets. The mean WBID value for 2001–2007 is only 0.22. Accordingly, the independent variable SHIFT (Table 2) allows for a shift in spectrum valuations in 2001. The impact of license award process variables on WBID values are of particular interest. Table 4 lists the conditional probabilities that a specified license award process variable is mandated, given that the associated winning bid value is above the sample mean. These data are for national market auctions held in 2001–2007 period. Thus, Table 4 identifies variables associated with 'high' WBID values during a period of stable spectrum valuations.

Table 4. Conditional Probabilities, 2001–2007

	$P(\cdot \mid WBID > \overline{WBID})$
ACTIVITY = 1	0.62
INFO = 1	0.46
NUMBER = 1	0.00
PACKAGE = 1	0.08
SEALED = 1	0.31

Table 4 indicates that auctions held during the 2001–2007 period with above average WBID values are 62% likely to have activity rules, 46% likely to have information available after each round and 31% likely to be sealed-bid. Interestingly, licenses with an endogenously determined number of licenses and package bidding have respectively, 0% and 0.8% probability of having above average WBID values. NRA-controlled license award process variables are further analysed to determine if common bundles of auction rules exist across countries. In particular, bivariate correlations are presented in Table 5.

Table 5. Selected License Award Process Variable Correlations, 2000–2007

	INFO	NUMBER	PACKAGE	SEALED
ACTIVITY	−0.01	0.23	0.25	−0.63
INFO		−0.47	−0.08	−0.14
NUMBER			0.40	−0.29
PACKAGE				−0.09

Of the ten reported correlations, nine are less than 0.5 in absolute value, with none greater than 0.63. This finding suggests that across countries distinct bundles of license award processes are employed. Such bundles may reflect particular NRA goals (e.g., revenue maximisation, market entry or network deployment). This variation enables the identification of variables that influence realized WBID.

4. Regression Model

The dependent variable WBID is censored with only winning bid values greater than the reserve bid price observed. That is, the observed price must not only be the largest value among all bidders, but must also exceed the NRA-specified minimum spectrum bid price. When the maximum bid (based on operator valuation) does not exceed the minimum spectrum bid price then the associated ‘observed’ price is zero. The regression model based on the preceding discussion is referred to as the censored regression model. The regression is obtained by making the mean of the censored model correspond to a classical regression model. The general formulation is usually given in terms of an index function:

$$\begin{aligned} y_{ij}^{*} &= x'\beta_{ij} + \varepsilon_{ij}, \\ y_{ij} &= 0 \text{ if } y_{ij}^{*} \leq 0, \end{aligned} \tag{1}$$

$$y_{ij} = y_{ij}^{*} \text{ if } y_{ij}^{*} > 0,$$

where $x_i = (1, x_{i1}, ..., x_{ip})'$ is a vector of p covariates which affect Spectrum Package i valuations and $\beta_j = (\beta_{j0}, \beta_{j1}, ..., \beta_{jp})'$ is a corresponding vector of parameters to be estimated. The stochastic component ε_{ij}, consists of unobserved factors that explain the marginal spectrum valuations of Operator j. Each ε_{ij} is drawn from a J-variate Normal distribution with zero conditional mean and variance, where $\varepsilon \sim N(0, \Sigma)$. For a randomly-drawn observation from the population, which may or may not be censored:

$$\mathrm{E}[\mathrm{y}_{\mathrm{ij}} | \mathrm{x}_{\mathrm{ij}}] = \Phi\left(\frac{\mathrm{x}_{\mathrm{ij}}'\beta}{\sigma}\right)(\mathrm{x}_{\mathrm{ij}}'\beta + \sigma\lambda_{\mathrm{ij}}), \tag{2}$$

where:

$$\lambda_{\mathrm{ij}} = \frac{\phi[(0 - \mathrm{x}_{\mathrm{ij}}'\beta)/\sigma]}{1 - \Phi[(0 - \mathrm{x}_{\mathrm{ij}}'\beta)/\sigma]} = \frac{\phi[\mathrm{x}_{\mathrm{ij}}'\beta)/\sigma]}{\Phi[(\mathrm{x}_{\mathrm{ij}}'\beta)/\sigma]}. \tag{3}$$

For the case with censoring at zero and normally distributed disturbances, the marginal effects in the censored regression model, are:

$$\frac{\partial E[y_{ij} | x_{ij}]}{\partial x_{ij}} = \beta\Phi\left(\frac{x_{ij}'\beta}{\sigma}\right). \tag{4}$$

The log-likelihood function for the censored regression model is:

$$\mathrm{Ln(L)} = \sum_{y_{ij}>0} -½\left[\ln(2\pi) + \ln\sigma^2 + \frac{(y_{ij} - x_{ij}'\beta)^2}{\sigma^2}\right] + \sum_{y_{ij}=0} \ln\left[1 - \Phi\left(\frac{x_{ij}'\beta}{\sigma}\right)\right]. \tag{5}$$

Finally, the estimated coefficients are comprised of both the impact of changes in the observed WBID and the probability any bid is a winning WBID value (McDonald and Moffitt, 1980). For coefficient values above the limit the marginal effects is scaled for the probability that the latent variable is observed.[9] Limdep calculates the conditional mean of the model at the mean of the independent variables to scale the coefficients.

5. Estimation

Estimation is via Limdep version 9.0. Table 6 reports joint significance tests for the explanatory variable categories: national economic and mobile market conditions; spectrum package attributes; network obligations; and license award process. The tests reject the null hypotheses that all the variable groupings are insignificant except for network obligations.

Table 6. Joint Significance Tests

Category	Variable	Wald statistic
National economic and mobile market conditions	INCOME MARKET MCOMP SHIFT	204.27***
Spectrum package attributes	DURATION ENTRANT RESERVE	83.36***
Network obligations	DEPLOY SHARE	1.16
License award process	ACOMP ACTIVITY INFO NUMBER PACKAGE SEALED	210.34***

Notes: *** significant at 1%. The above categories are tested as they contain several variables.

The censored regression model estimates reported in Table 7 indicate a significant Lagrange Multiplier test of model restrictions. Also, ANOVA (22%) and DECOMP (35%) fit measures show improvement in the log-likelihood relative to the restricted model.

[9] Limdep provides a scale factor, analogous to the sample proportion of observations above the limit, to compute the marginal effects of the independent variables (Greene, 2008).

Table 7. Censored Regression Estimates

Category	Variable	Coefficient	Marginal Effect
	Constant	–3.602***	
		(0.917)	
National economic and mobile market conditions	INCOME	0.000*	0.000*
		(0.000)	(0.000)
	MARKET	0.000***	0.000***
		(0.000)	(0.000)
	MCOMP	1.662	1.645
		(1.358)	(1.345)
	SHIFT	–2.433***	–2.408***
		(0.198)	(0.197)
Spectrum package attributes	DURATION	0.236***	0.234***
		(0.036)	(0.036)
	ENTRANT	0.138	0.136
		(0.172)	(0.170)
	RESERVE	0.000*	0.000*
		(0.000)	(0.000)
Financial obligations	PERCENT	–0.077	–0.076
		(0.101)	(0.100)
Network obligations	DEPLOY	0.737	0.730
		(0.754)	(0.747)
	SHARE	0.033	0.033
		(0.222)	(0.220)
License award process	ACOMP	0.737***	0.730***
		(0.103)	(0.102)
	ACTIVITY	–0.412**	–0.415**
		(0.167)	(0.165)
	INFO	0.530***	0.525***
		(0.165)	(0.163)
	NUMBER	–2.168***	–2.145***
		(0.211)	(0.210)
	PACKAGE	0.205	0.203
		(0.153)	(0.151)
	SEALED	–0.039	–0.038
		(0.220)	(0.217)
	N	81	
	ANOVA	0.81	
	DECOMP	0.93	
	Log likelihood	–38.15	

Notes: Standard errors in parentheses. * significant at 10%; ** significant at 5%; *** significant at 1%.

Turning to the impact of the explanatory variables on the 3G winning bid value (WBID), several distinct patterns emerge from examining Table 7. Firstly, most national economic and mobile market condition variables are individually significant in explaining winning bid behavior. In particular, higher winning bids occur for licenses with a larger national market (MARKET = 0.000) and higher per-capita income (INCOME = 0.000). These results are consistent with the predictions of pricing theory as well as the outcomes of early 3G auctions.[10] Moreover, WBID values are lower post-2000 (SHIFT = –2.408). The observation that the time sequence of national 3G auctions matters is established by Klemperer (2003). Klemperer argues that during the year 2000 auctions while more entrants participated; some bidders are 'weak'. Klemperer argues that the non-collusive behaviour of naive strong bidders in early auctions is the reason for the observed sequence of declining bids. According to Klemperer (2002b), "the UK sale taught firms the costs of participating in a competitive auction, and they became increasingly successful at forming joint ventures that ensured the subsequent auctions were less competitive." Another argument by Klemperer is that intertemporal complementarity between early and later auctions in that early wins strengthens the position of incumbents opposing potential entrants in later auctions. Clearly, this dynamically induced asymmetry between bidders in later auctions reduces competition and winning bid premiums. Also noteworthy is that the effect of MCOMP on WBID is insignificant, i.e., the number of national facilities-based operators does not affect the winning bid.[11] This outcome contrasts with the prediction that the fewer facilities-based operators (higher MCOMP value) in a market, the more bidders for a license, hence higher WBID values.

For variables describing spectrum package attributes, both length of license and reserve price matter (DURATION = 0.234 and RESERVE = 0.000). Importantly, license duration is specified by NRAs in tender documents. Thus, the positive sign for DURATION is consistent with the predicted positive association between the winning license bid and license value to the winning bidder. The reported positive sign of RESERVE is consistent with the view of Klemperer (2002a) and Cramton (2004) that sufficiently high reserve prices discourage collusion, as well as, with the claims of Cramton (2002) that high reserve prices lower the

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[10] Cramton (2001) argues that part of the difference in the winning bids observed in the early European 3G auctions (UK, Germany vs. Netherland, Switzerland) is explained by the per capita size of the markets.

[11] A facilities-based operator has a licence that allows the deployment of any form of telecommunication networks and facilities by any persons to provide telecommunication services to third parties.

incentive for demand reduction in a multiple-item auction and reduce the number of rounds that bidders have to coordinate a split of licenses without increasing bids.

Additionally, the spectrum package variable ENTRANT is not significant (10%) which contrasts with the claim that by awarding at least a single license to a non-incumbent firm the auctioneer expects to attract more (new) bidders and so receive higher winning bids. For instance, in the UK auction (most successful 3G auction), which guaranteed license availability to one new entrant, attracted nine such bidders and four established incumbent firms. Should the number of licenses equal incumbent numbers, it is not unlikely that some potential entrants will participate independently or partner with an incumbent bidder (the latter is the case, e.g., in the Netherland's unsuccessful 3G auction). Inadequate competition between bidders is more severe when an auction is ascending. In this situation potential entrants are strategically disadvantaged when bid information is revealed by round. While the auctioneer can attenuate the insufficient entry problem by choosing an Anglo-Dutch auction, such hybrid auctions are rarely used in 3G spectrum markets.

Table 7 indicates that the mean annual license fee (PERCENT) imposed by NRAs as a post-award financial obligation is not important in the decision calculus applied by MNOs in bidding. Network obligations imposed on operators by NRAs are DEPLOY (percentage of population to be covered and years to achieve network coverage) and SHARE (required sharing of network infrastructure), which are also potentially important.[12] Increases in DEPLOY plausibly augment expected operator profit, when DEPLOY is below the optimal operating scale. Given that DEPLOY is reported insignificant, it may be the case that DEPLOY is binding for some of the potential bidders, or else for a substantial part of the licenses, population is widely dispersed in covered regions. As for SHARE, Binmore and Klemperer (2002) argue that the SHARE obligation eliminates (or reduces) the cost advantage of incumbents (already operate 2G licenses) over potential new entrants, attracting bidders and making higher winning bids more likely. Conversely, infrastructure sharing reduces the value of an auctioned license from an incumbent's perspective. Indeed, conflicting views of incumbents and potential entrants on infrastructure sharing may explain the insignificant impact of SHARE on the winning bid. Finally, more spectrum competition

[12] It should be noted that the effect of DEPLOY on WBID cannot be predicted independently of two related attributes, namely the planned optimal (minimum efficient) operating scale of the potential bidders and the dispersion of population in a given country, which are not contained in the dataset.

(ACOMP = 0.730) increases WBID. The importance of the number of bidders per license for the success of an auction is emphasized by Klemperer (2002a) in his evaluation of the European 3G auctions.

Interestingly, the incidence of NRA-specified auction design variables, e.g., activity rules (ACTIVITY = –0.415), information sharing (INFO = 0.525) and endogenously determined licenses (NUMBER –2.145) impact on WBID. The common part of the activity rules announced in 3G auctions require bidders to submit active bids for the auctioned license (or on some minimum number of frequency packages) to not be disqualified. Such rules aim to prevent delayed bidding (concealing information) by firms and increase expected revenue. However, the estimated negative sign of the regression coefficient of ACTIVITY suggests that other activity rules (e.g., German and Austrian auctions), such as limiting the number of frequency blocks/packages that firms can bid and bounding the maximal number of active bids in any round from above by the number of active bids in the previous round, may depress competition between non-collusive firms.

The estimated positive impact of INFO on WBID is expected since publicly announced bid information, including the identity of bidders and their bids, after every round reduces bidders' private information, hence informational rents. Table 7 also shows that (flexible) NUMBER (of licenses) adversely affects seller revenue. A common belief is that auctions are most profitable from the seller's viewpoint when there are more licenses than incumbents.[13] The main reason for this belief is cost asymmetry faced by the incumbents and potential new entrants in building 3G networks, with incumbents able to use 2G infrastructures to provide 3G services. The fear of losing profit from existing 2G services to potential entrants aggravates this asymmetry.[14] To address strategic incumbent advantage, some NRA's (e.g., Austria, Germany and Italy) employed auction designs that allow flexible license numbers and capacity allocations. However, most of these designs proved unsuccessful. For a spectrum block involving 2x10 MHz + 5 MHz, the (per capita) revenue raised in the Italian case (US$ 35.2) is a third of the revenue (US$ 107.2) from the UK auction, while the revenue from the Austrian auction is lower at US$ 15.3.[15] Jehiel and Moldovanu (2000) are critical of

[13] This belief is not invalidated by the observation that in the most successful telecommunications auction (the UK) the exogenously set number of licenses exceeded the number of incumbents by 'one'.
[14] For a discussion on the strategic advantage of incumbents against possible new entrants in the auctions for 3G spectrum licenses, see Jehiel and Moldovanu (2000).
[15] See Cramton (2001) for a comparison of the early European auctions to the UK auction.

the flexible license number specifications in the German auction. Jehiel and Moldovanu argue that while this design enticed entry by two new firms (and four incumbent bidders), the auction favoured incumbents and yielded lower revenue. The design endogenized bidder values unintentionally and gave incumbents an incentive to pre-empt entry by new bidders.

Of the license award process variables, PACKAGE (bidding), which is used in 27% of the spectrum auctions in the sample, is insignificant in explaining winning bids. Auction theory suggests that with complementarity, it is more profitable for sellers to auction licenses in packages using a 'combinatorial auction'.[16] That is, when there is bidder complementarity between licenses, the sequential (or simultaneous) auction of licenses separately leads to an 'exposure' problem. Namely, bidding for complementary licences is risky since bidders may not win all desired components. Thus, the exposure problem suppresses competition. Package bidding solves the exposure problem but introduces additional problems. First, package (combinatorial) auctions are complex to analyse for bidders and sellers. Choosing an optimal bidding strategy and determining the winner are difficult computational problems. Second, Cramton (2004) argues that combinatorial auctions favour bidders seeking large packages. Therefore, package bidding probably leads efficiency and revenue loss. Given the insignificant impact of PACKAGE on winning bids, it is reasonable to argue that complementarity between licenses is not important or that package bidding problems may outweighed benefits.

Finally, the effect of SEALED on WBID is unclear. Auction theory suggests that more entrants and higher returns are expected under sealed-bid auctions than non-sealed (mostly ascending) simultaneous auctions (proposed by Paul Milgrom, Robert Wilson and Preston McAfee), since collusion is harder in sealed-bid auctions as bids cannot be used as signals (Klemperer 2002a). Additionally, when bidders have common license values the winner's curse is less severe for potential weak bidders in sealed-bid auctions. This circumstance makes weak bidders more willing to enter sealed-bid auctions and bid more aggressively, leading to higher winning bids (Klemperer 1998; Bulow et al. 1999). Besides, when bidders are risk averse, open-bid (first price) auctions yield more revenue than ascending auctions. Furthermore, the sealed-bid format is less vulnerable to demand manipulation than the

[16] For a thorough discussion on package bidding, see Milgrom (2004).

simultaneous ascending format (used in most spectrum auctions).[17] Conversely, where license value signals are affiliated (Milgrom and Weber 1982) sealed-bid auctions are less profitable than ascending auctions if bidders are symmetric, risk-neutral and not budget-constrained. Klemperer (2003) explains that sealed-bid auctions are inferior when signals about values are affiliated by observing that bidder profits derive from private information and that sealed-bid auctions (unlike ascending auctions) do not reduce private information. As SEALED does not explain WBID, it is not possible to reject the hypothesis that diverse predictions of auction theory about the impact of SEALED may have occurred in this sample of 3G auctions.

Table 8 contains elasticity estimates for policy relevant (under NRA control) variables. Elasticity values (evaluated at the sample mean of the independent variables) that are either elastic (or near elastic) have a more important impact on operator auction bidding behaviour. The DURATION elasticity value suggests that when the license duration increases by 1% above the mean there is a 4.756% increase in WBID value (increase in the perceived value of the license to the winning bidder). Additionally, the ACOMP (auction competition) elasticity indicates that a 1% increase in auction competition leads to a 1.001% increase in WBID values. The absolute values of the estimated elasticities for RESERVE, ACTIVITY, INFO and NUMBER are less than unity in absolute magnitude. In particular, higher reservation prices (RESERVE) or the incidence of mandated information sharing (INFO) result in higher winning bids. Moreover, the incidence of mandated activity rules (ACTIVITY) or endogenous license number (NUMBER) decrease winning bids.

[17] Cramton (2004) addresses the problem with simultaneous ascending auctions whereby when competition for the auction is weak, bidders (incumbents) have an incentive to reduce their demands to keep the price low.

Table 8. NRA Control Variable Elasticity Estimates

Category	Variable	Elasticity
Spectrum package attributes	DURATION	**4.756**
	ENTRANT	0.019
	RESERVE	**0.072**
Financial obligations	PERCENT	–0.019
Network obligations	DEPLOY	0.099
	SHARE	0.012
License award process	ACOMP	**1.001**
	ACTIVITY	**–0.290**
	INFO	**0.228**
	NUMBER	**–0.451**
	PACKAGE	0.062
	SEALED	–0.009

Note: Bold indicates the coefficient is significant.

6. Conclusions

This paper attempts to identify the determinants per capita revenue from national 3G spectrum auctions. Sample per capita winning bids are regressed on national economic and mobile market conditions, spectrum package attributes, network obligations and license award process variables. Censored model estimation establishes that most of the economic and mobile market conditions are individually significant; licenses auctioned before the year 2001, auctioned in countries with larger national markets or with higher per-capita income yield on average higher revenue. Of spectrum package attributes, license duration and reserve price are significant. But, neither the post-award financial obligation (mean annual license fee) nor post-award network obligations (percentage of population to be covered, and whether infrastructure sharing is required) explain winning bid values. Interestingly, most of the license award process (ratio of bidders to auctioned licenses, availability of an activity rule, publicity of the bid information during the auction, and flexibility of the number of licenses) variables are significant. Only the availability of package bidding and the format (sealed or open) of bids are insignificant.

A limitation of the analysis is the sample does not allow the testing of several interesting propositions that are potentially important. In particular, whether the availability of the resale option or use of hybrid (Anglo-Dutch) auctions affects realised auction revenues. Klemperer (2002a) argues that an ability to resell licenses attracts more entrants in sealed-bid auctions. Klemperer also claims that, in situations where the number of licenses does not exceed the incumbents' number, more revenue is likely generated by auctions with a hybrid (Anglo-Dutch) format than by the pure Anglo (ascending bid) or pure Dutch (sealed bid) formats.[18] For the period 2000-2007, only Czech Republic and Nigerian NRAs apply this mixed design. Another interesting hypothesis, due to Klemperer (2002a), that requires additional data to consider auctions where the number of bidders relative to available licenses is 'large'. In this situation auction design variables (license award processes) are immaterial. For the current sample the number of available licenses per bidder exhibits little variation (0.39) around the mean value of 0.99. Finally, further analysis is required to examine the impact of auction design, national economic and mobile market conditions, spectrum package attributes and network obligations on 'pre-award' competition for the auctioned licenses. Such analysis would provide a better understanding of the impact of auction design variables on realised auction revenue.

7. References

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[18] Anglo-Dutch format was introduced by Binmore and Klemperer for the UK 2000 auction to attract more entrants (by the presence of the sealed-bid, Dutch, stage) and to increase the amount of the winning bids (by the ascending-bid, English, stage) in case the number of incumbents and the number of licences are equal. However, this hybrid design was not used in the UK market with four incumbents as it occurred before the auction started that there was an additional licence available for potential new bidders.

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